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The Mercury Laser System: An Average power, gas-cooled, Yb:S-FAP based system with frequency conversion and wavefront correction

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Abstract

We report on the operation of the Mercury laser with fourteen 4 x 6 cm^2 Yb:S-FAP amplifier slabs pumped by eight 100 kW peak power diode arrays. The system was continuously run at 55 J and 10 Hz for several hours, (2x10^5 cumulative shots) with over 80% of the energy in a 6 times diffraction limited spot at 1.047 um. Improved optical quality was achieved in Yb:S-FAP amplifiers with magneto-rheological finishing, a deterministic polishing method. In addition, average power frequency conversion employing YCOB was demonstrated at 50% conversion efficiency or 22.6 J at 10 Hz.

1. INTRODUCTION

Hundred-joule, kilowatt-class lasers based on diode-pumped solid-state technologies, are being developed world-wide for applications in laser-plasma interactions and as prototype systems for fusion energy systems. The goals of the Mercury Laser Project are to develop the key technologies at sub-scale energies and beamline apertures, within an architectural framework that represents building blocks of larger multi-kilojoule systems for inertial fusion energy applications.

The Mercury Laser architecture incorporates a gas-cooled amplifier geometry for heat removal from the faces of fourteen Yb:S-FAP slabs distributed within two amplifiers. Both amplifiers are optically pumped by high brightness diode arrays totaling 800 kW of peak power at 900 nm. The four pass laser system has been configured to minimize intensity modulation at the amplifiers, optical switch and adaptive mirror. To minimize parasitics in the amplifiers, an average power Pockels cell is employed after two passes. At the output, the beam is relay imaged to an average power frequency conversion module and converted to the second harmonic. Both highly deuterated KDP (DKDP) and YCOB have been tested at 10 Hz.

The system has been configured with a full suite of automated diagnostics, data archiving software, and integrated safety systems for 10 Hz operation. Future plans for the laser include laser-plasma interaction experiments and designs for multi-kilojoule scaled versions of the Mercury laser architecture. These designs have a set of challenging requirements that include: high efficiency, stringent reliability, and availability for large (10^9) shot counts.

2. ARCHITECTURE

The Mercury architecture utilizes a diode end-pumped scheme in which the diode light and laser light are co-propagating. Each amplifier assembly is pumped by two set of 100 kW diode arrays to provide 12.3 nepers of total gain for 100 J of output. The diode light is first angularly redistributed by hollow concentrating optics to a 3x5 cm aperture in which the angular divergence of the beam is made nearly identical in both the x and y axes. The diode light is then guided by a rectangular reflective cavity called a ‘homogenizer’, which maintains the angular distribution while smoothing the spatial pump profile. The face-cooled helium gas amplifiers efficiently remove 1-3 W/cm^2 of heat with minimal thermal wavefront distortions.

The beamline architecture employs an off-axis, four-pass configuration whereby each pass utilizes custom pinholes tailored in size to optimally filter while accommodating high power. To avoid needing a full power optical switch, the beam is propagated at eight – milliradians relative to the optic axis allowing beam separation near focus and passive 4-pass amplification. To reduce buildup of parasitic beams, a birefringence-compensated Pockels cell is used after two passes where the average power is less than 200W. The 3.5 x 6 cm

Pockels cell was fabricated with highly deuterated KD*P (Inrad Corp.) to minimize optical absorption and subsequent thermal loading. The measured static contrast of the Pockels cell is greater than 200:1 with less than 0.15 static peak to valley wavefront distortion. The rise and fall times are less than 11 ns and are driven by the pulser technology. To increase reliability and minimize the probability of optical damage, relay imaging with vacuum telescopes is used. In addition, the amplifiers and one lens of the telescope is located near a relay plane.

The computer controls and data acquisition are nearly automated for 10 Hz laser operations. A suite of diagnostics allows the beam to be interrogated on each pass. In particular, real-time observation diagnostics and image differencing algorithms (near field and a dark field), allow rapid detection of beam inclusions (dust or damage) at 10 Hz. When the computer software algorithm detects an obscuration (> 100 μm) a signal is sent to the control system to terminate operations by the next shot.

3. LASER DIODES

The Mercury high power laser diode arrays are fabricated with bars manufactured by Coherent Inc. The emission wavelength is centered at 900 nm (2.2 nm bandwidth) to match the S-FAP absorption feature. The bars are soldered onto precision etched silicon for heat transfer. The etched V-grove geometry also provides a means of precisely registering of the laser diode bars with respect to the microlenses [2]. The microlenses are glued onto silicon rails and mounted onto the 23-bar silicon heatsinks forming a "tile". Thirty-six tiles are secured onto a large water cooled copper block with cooling manifolds and feed through slots for electrical power. The angular divergence of an array is 150 mrad by 15 mrad, which closely matches the divergence of a single bar. Nearly 2 million system shots have been accumulated on the diode arrays. Offline life tests on single diode array tiles have demonstrated lifetimes greater than 10^8 shots.

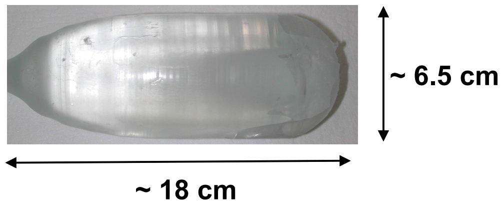
4. GAIN MEDIA AND GAS COOLING

Yb:S-FAP crystals have many attractive laser properties that make them well suited for diode pumping in moderate thermal load applications. In particular, Yb:S-FAP offers relaxed diode brightness requirements compared to other Yb-based media, a long pump lifetime of 1.14 msec, and a saturation fluence (3.1 J/cm^2) suitable for nsec pulse extraction. In the last ten years, a collaborative effort has developed between Lawrence Livermore National Laboratory and Synoptics at Northrop Grumman to grow and scale high quality boules for the Mercury laser operation [3].

The Mercury Laser, as currently configured, requires a minimum of 14 Yb:S-FAP slabs for operation. Each slab has dimensions 4 cm x 6 cm x 0.75 cm in thickness, where the c-axis is oriented along the 6 cm length of the slab. Crystals are grow using the Czochralski method. Currently, the growth of large, high optical quality, 7.0 cm diameter crystals is the focus for the Mercury laser as shown in Fig. 1a. Grain boundaries and bubble core are the main defects being addressed in these larger crystals. Significant progress has been made toward reducing or eliminating each of these defects to produce high quality material.

At this time, 14 slabs populate the two amplifier heads and 20 spares are in fabrication. An important step in fabrication involves improving the transmitted wavefront through Magneto Rheological Finishing (MRF) and increasing the damage threshold by reducing subsurface damage. MRF is used to soften any remaining defect features within the slab, such as index distortions around grain boundaries or strain in the crystals (Fig. 1b) [4]. Improvements in polishing and crystal quality have increased damage initiation thresholds to greater than 13 J/cm^2 and damage growth thresholds to greater than 30 J/cm^2 for a 3 ns pulse at 1064 nm (test wavelength).

The final slab preparation step before installation in the laser is to mount the slabs into aerodynamic structures called "vanes", which are used in the high speed gas-cooling thereby enabling the 10 Hz operation. The vanes are first lined with a highly absorbing edge cladding (Schott KG5 glass). The slabs are then potted into the vanes utilizing an elastomer which transmits diode and laser light to the edge cladding while at the same time providing a compliant insulating barrier to protect the slab from thermal and mechanical stresses. The vanes are then mounted together to form the amplifier line replaceable unit (shown Fig. 1c) where each vane is separated by one-millimeter wide helium gas cooling channels. Helium was chosen for its low index of refraction and efficient cooling properties. At 50 psi and 0.1 Mach flow, the cooling system removes 1-3 W/cm^2 from the faces of each slab. The amplifier heads were each tested for flow compliance and found to have less than 0.12% rms deviation between gas channels. The turbulent gas flow over the surface of the slabs provides a longitudinal thermal gradient which is manageable for average power operation. In the the case of uniform pumping. all points on the beam, to first order, see the same set of thermal gradients. The amplifier heads were successfully tested at 20% beyond the designed thermal load (Fig. 1d). The net wavefront was 0.95 waves of distortion per amplifier head. These results are encouraging because the proposed thermal load at multi-kilojoule apertures (> 10 cm) with the required pump uniformity is less due to decreased edge effects.



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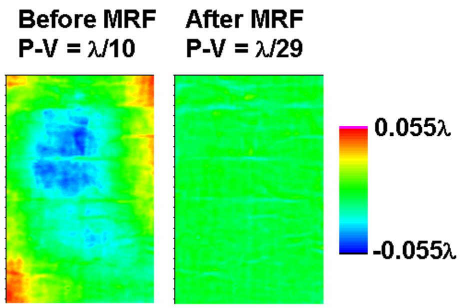

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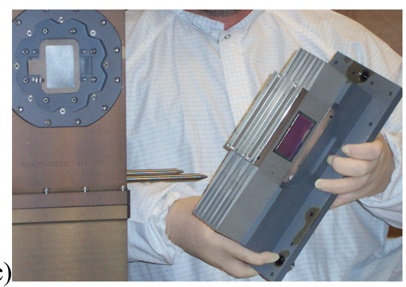
c) 

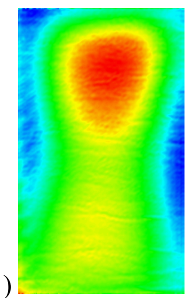
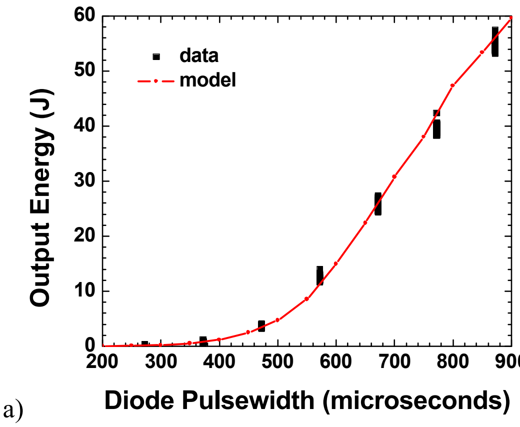
d) 

Fig. 1a) A large diameter S-FAP boule yields two full size 4x6x0.75 cm amplifier slabs, b) MRF improves peak to valley wavefront distortion, c) complete gas-cooled amplifier head with vanes removed showing aerodynamic structure, and d) thermal wavefront distortion is less than 0.95 waves at full power.

5. LASER EXPERIMENTS at 1 um

The most recent set of experiments focused on demonstrating the system at half power. The gain was increased by holding the front end energy constant (10 mJ) and increasing the diode pulse length from 300 to 900 μsec (Fig. 2a). At each operating point the system was tested for parasitics and ASE losses. The collection of data allowed a full mapping of the system gain. Due to the long lead time to acquire an average power adaptive optic, a fused silica corrector plate fabricated with MRF technology. The plate was imprinted with 3.4 waves of correction to compensate for cavity optics and residual distortions in the amplifier.

The front-end system provides temporal pulse shaping to compensate for the gain distortions and allows a nearly square pulse in time to be formed at the output. At 55 J output a square input pulse is significantly distorted by gain saturation that produces a peak at the leading edge of the pulse. By utilizing a arbitrary waveform generator (Highland Technologies), the input temporal pulseshape was sculpted to produce a square output pulse at 55 J (Fig. 2b). After single shot verification at this level, the repetition rate was increased to 10 Hz. After several hour runs at both 1 Hz and 5 Hz, the system was run at the 10 Hz design point with a 55 J output for a total of seven hours (Fig. 2c). The rms fluctuation in energy over this operation was 3%, with more than 80% of the energy in a 6 times diffraction-limited spot.



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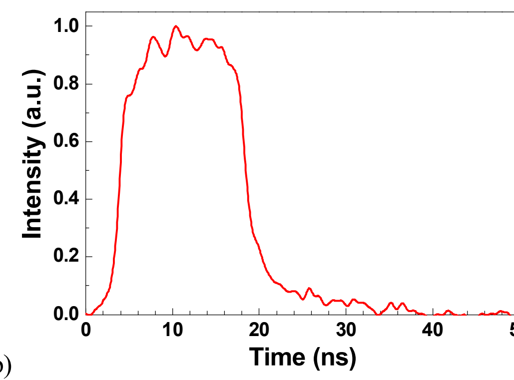

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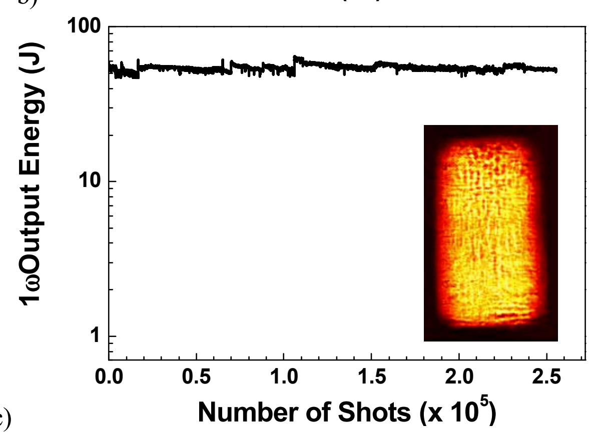

c)

Fig. 2 a) Energetics gain curve showing agreement with model, b) 15 ns FWHM shaped output laser pulse, c) average power operation at 55 J for over 2.5 x 10^5 shots.

6. ADVANCED TECHNOLOGIES

Several beam control technologies have been developed in the last year including: average power frequency conversion, a temporal, spectral, and spatially sculpted front-end upgrade, and a deformable mirror for active wavefront control.

6.1.1 Average Power Frequency Conversion

In contrast to the gain medium, nonlinear optical processes are elastic processes, with the thermal load arising strictly from residual linear and nonlinear absorption in the crystal. Typical absorption for transparent crystals is on the order of 0.0025/cm, leading to an average power loading of 0.01 W/cm^2. These modest thermal loads lead to relatively small temperature gradients of 2-3 degrees C in the nonlinear optical crystal. Nevertheless, this gradient can lead to thermal dephasing (reduced conversion efficiency) or thermal fracture. An adaptation of the current gas cooling technology for frequency conversion would require modifications to introduce angular tuning capability. A typical pointing specification for critically phasematched crystals is 250 μrad, while the typical crystal vendor orientation capability is on order of 17,000 μrad thereby requiring the ability to individually rotate the crystals with respect to the beam propagation direction.

Although gas cooling would work for frequency conversion the necessity for angular tuning makes this method unnecessarily complex for the initial proof of principle stages. Another technology, recently utilized in an externally doubled high average power laser [5], has been examined. This cooling technique relies on a highly thermally conductive and transparent substrate. We have chosen sapphire since it is widely used as an optical window substrate and has a relatively high thermal conductivity (30 W/m/K). The frequency conversion cooler concept (Fig. 3a) currently combines close coupling of the crystal to the sapphire plate and has been shown to scale to the required 20 cm aperture.

We have also scaled the growth of YCOB to the 5.5 x 8.5 cm^2 apertures necessary for the Mercury laser. In addition to its enhanced thermo-mechanical properties, YCOB also has 3 times the d_{eff} relative to KDP, another large aperture nonlinear material [6]. In the first full power frequency conversion experiment, the Mercury output beam was image relayed to a side-cooled uncoated YCOB crystal 1.58 cm thick. We demonstrated a world-record 225 W of average power 523 nm light for over 30 minutes at a drive of 550 W at 1047 nm. Over 3x10^4 shots at a drive of over 0.1 GW/cm^2 was incident on the crystal without any observable damage or thermal dephasing. As shown in Fig. 3c, the experimentally measured conversion efficiency agreed with calculations that taken into account the angular acceptance of YCOB, the lack of an AR coating on the YCOB crystal, and the measured beam quality.

In upcoming experiments, when the Mercury laser achieves an output of 75 J at 1047 nm, the optimal thickness of YCOB will be reduced to about 9 mm. The drive at 10 ns will be around 0.2 GW/cm^2 and the expected frequency conversion will be 70%.

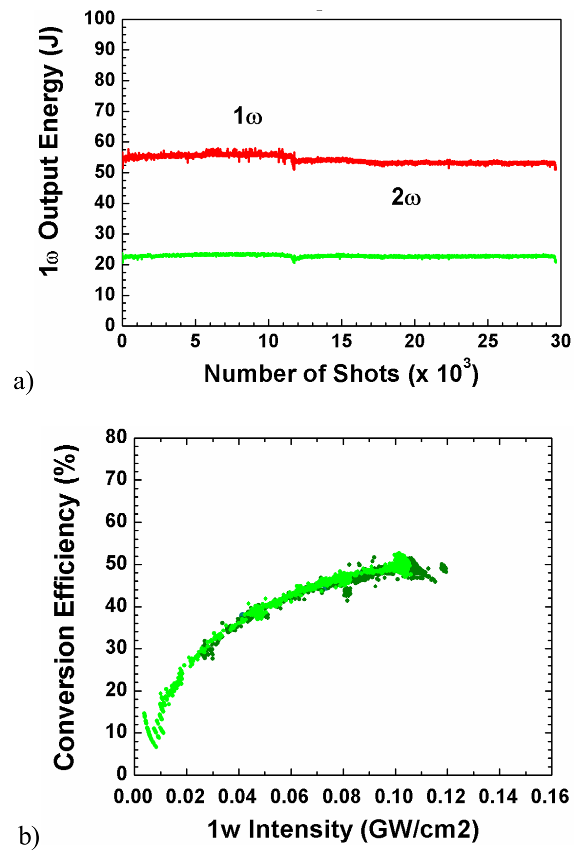

Fig. 3 a) Average power frequency conversion at 225 W, 22.5 J @ 10 Hz for > 30 min., b) Conversion efficiency as a function of pump intensity

6.1.2 Front End System with Bandwidth

We are developing a 500mJ, 10 Hz front-end laser system with flexibility in temporal, spectral, and spatial sculpting. The output pulse width can be varied from 2 to 15 nanoseconds and with the appropriate intensity contrast to compensate for square pulse distortion. To demonstrate beam smoothing capabilities at average power, the addition of bandwidth occurs at the low energy stages and is accomplished by double passing the beam through a lithium niobate phase modulator. This device is capable of supplying RF bandwidth up to 250 GHz. The modulation side bands are individually attenuated to compensate for the gain profile in SFAP, thereby minimizing amplitude modulation resulting from gain-narrowing of a frequency modulated spectrum. The front-end system is fiber-based with an oscillator, small amplifier, and three gain modules that use a large mode area ytterbium doped fiber. The output (30 μJ) is then injected into a Yb:S-FAP ring configuration and amplified to 500 mJ.

To date we have demonstrated the operation of the complete fiber system. This system incorporates closed-loop temporal shaping and has run with up to 250GHz of bandwidth. The two diode-pumped Yb:S-FAP multi-pass ring amplifier modules have been characterized. Each module demonstrates a small signal gain of 3.2 which matches model predictions. In the near future, the two systems (fiber preamplifier and Yb:S-FAP modules) will be integrated and tested.

6.1.3 Deformable Mirror

The high average power operation of the Mercury laser will induce dynamic aberrations to the output beam wavefront and far field. Recent wavefront measurements of the system showed that up to 4 waves per pass of low order aberration are expected. A 10 cm diameter bimorph deformable mirror with 41 actuators (1 cm spacing) has been designed. An advantage of the bimorph deformable mirror is that the outer actuator can compensate powers of up to 20 waves. Damage tests of the coating witness sample showed no damage up to 5 J/cm^2 (the max. expected fluence is 1.5 J/cm^2). The reflectivity of the coating was measured to be 99.98%, implying that very little light will penetrate into the substrate. As a result, cooling of the DM is not necessary. Modeling of the DM using the response matrix of the actual hardware predicts that after correction there will be a residual RMS deviation of 0.05 waves up to a 0.5 cm^{-1} spatial frequency limitation.

6. SCALING

A critical goal of the Mercury laser project is to demonstrate the technologies necessary for scaling up to multi-kilojoule apertures relevant for IFE. The next steps require increasing the aperture to a full IFE beamline, demonstrating diode cost reduction, and incorporating beam bundling.

The laser diodes currently used on the Mercury laser were developed in 2001 and have an output power of up to 150 Watts per bar with a wall plug efficiency of roughly 45%. Since 2001, the diode industry has made great improvements in both power and efficiency, demonstrating up to 270 W diode bars in a recent test of advanced bars (Coherent Inc.,) and up to 73% wall plug efficiencies [7]. Over the last 10 years the $/W has continued to drop and appears to follow a 59% learning curve.

Scaling of the Yb:S-FAP and YCOB crystal apertures has already begun, with test growths to occur later this year. In addition, we are examining a modified Bridgeman crystal growth technique that has previously demonstrated 40 cm apertures in CaF_2, as well as ceramic manufacturing methods for scaling the aperture.

One of the major concerns in building and fielding an IFE power plant is minimizing cost and maximizing operation time over the life of the plant. To achieve these goals, we are studying the long-term effects of high average power on optical components, as well as system level studies of beam availability versus number of beamlines, architecture, and beam bundling. In addition to the core technologies needed for the driver, many of the controls, support equipment, diagnostics, and alignment capabilities for a complete IFE facility need to be developed to provide a high mean time between failure.

Finally, in pursuit of our IFE mission, we will begin fielding a series of high energy density physics experiments. The first experiments planned include damage tests of final optic candidates and an “Extreme chemistry – ultra high pressure” experiment which investigates material structural properties at Mbar pressures.

Acknowledgements

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